

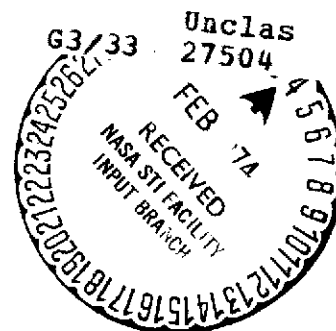
BASIC EXPERIMENTS IN TEMPERATURE REGULATION

J. Aschoff

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16. Abstract A method is described by which characteristic values which permit a numerical comparison between various heat transmission conditions can be obtained from the cooling curves for a body in a flow calorimeter. The cooling values are calculated as the slope of a straight line which is obtained from a logarithmic plot of the measured caloric values versus time. These cooling values can be used to compare different heat transmission conditions for various bodies with one another in the cooling experiment which is described, involving a flow calorimeter into which a hand, or a model of a hand, can be immersed; the inlet and outlet water temperatures are taken by means of thermocouple elements and are plotted with a continuous recorder.			
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BASIC EXPERIMENTS IN TEMPERATURE REGULATION

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* * *

Thus the transmission of heat can be affected both by varying heat transfer and by varying the "coefficient of heat transport" [$\text{Kcal}/(\text{m}\cdot\text{h}\cdot\text{C}^\circ)$]; the latter is affected in turn by variations in the coefficient of thermal conductivity or in convective heat transport.

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Flow calorimeters (Fig. 1) fed from overflow reservoirs were used to study a number of questions associated with the above. Number of calories given off calculated by multiplying flow volume per unit time, held constant, times the temperature difference between inflow and outflow in each case. The vessels were open at the top so that models or hands could be quickly dipped into the flowing water. Inflow temperature between 11° and 12° ; flow rates between 100 and $300 \text{ cm}^3/\text{min}$.

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An example of the temperature differences, recorded photographically, is given in Fig. 2. The initial reading after opening of the galvanometer short circuit indicates heating of the circulating quantity of water by its surroundings. This "calorimeter blank value," recorded for several minutes, serves as the base line for subsequent evaluation. The rise in the temperature curves after submersion of hands manifests the sluggishness of the system, which makes the quantities of heat given off determinable only after 3 to 5 min, depending upon flow rate. The order of magnitude of this latency period is a function of the hand:calorimeter volume ratio and of flow rate. If the

* Numbers in the margin indicate pagination in the foreign text.

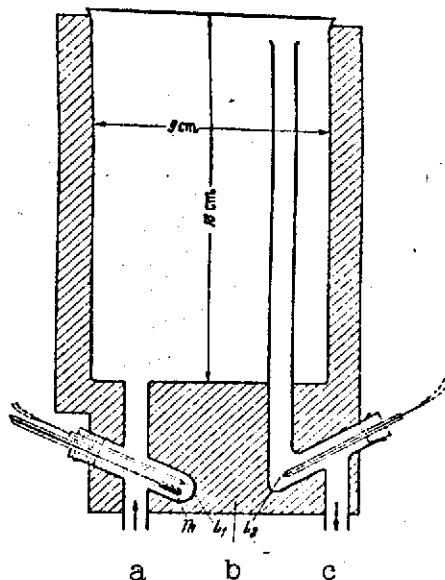


Fig. 1. Flow calorimeter. L_1 and L_2 : thermocouple elements for measuring temperature difference between inflowing and outflowing water. Th : mercury thermometer for checking inflow temperature. Vessel capacity 950 cm³.

Key: a. Inflow; b. Thermal insulation; c. Outflow

or determined planimetrically over a period of several minutes. Values with less than 0.3° heating are not considered, due to the relatively large possibility of error. The calory values obtained are converted to 1 unit surface area in all cases; all data given in Kcal/(m²·h).

2. Model Trials Under Normal Conditions

A model hand of glass was prepared to first provide an idea of the behavior of a simple physical body in this setup. Its relatively regular form made the surface area mathematically determinable to an approximate degree. Dimensions of the model

volume of the hand is assumed to be 350 cm³, the remaining calorimeter capacity of 600 cm³ is flushed through in 3 min at a flow rate of 200 cm³/min; the curve can be evaluated after this time has elapsed, at the latest. Response time for the thermocouple element / galvanometer setup, 2 and 6 sec, can be neglected here. Scales included in Fig. 2 indicate the extent of heating of the water at any instant, which obviously decreases continuously with increasing cooling of the hands.

The number of calories given off was determined by multiplying volume of flow per unit time by the average heating values read off directly at 1-minute intervals

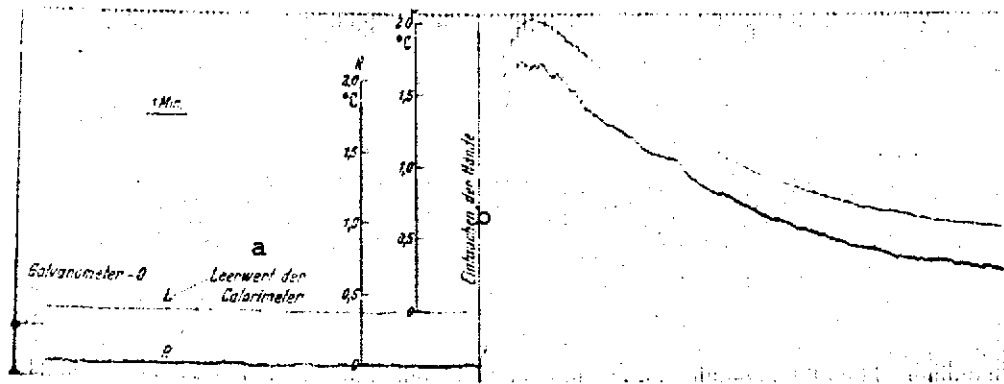


Fig. 2. Original curves of a trial with both hands dipped into the calorimeter, 200 cm³/min flow rate. Inflow temperature 11.0°. Ambient temperature 18.2°. Time marks every 10 sec.

Key: a. Calorimeter blank value
b. Hands immersed

hand: volume 250 cm³, surface area 317 cm², wall thickness 1.3-1.4 mm, volume:surface 0.79. The hand, filled with water at a known temperature, was closed with a stopper at the "wrist" and placed in one of the calorimeters. A reduction, with time, of water heating from 2.0° to about 0.3° could be satisfactorily followed in the recorded temperature curves at the level of sensitivity built in to the system.

The quantities of heat given off by the glass hand (Fig. 3) are at first a function of the initial temperature difference, of course, as manifested in the displacement of the curves to the right as heat content increases. The very much flatter curve for the right hand, presented here only for comparison, providing an indication of lower heat transmission, is discussed elsewhere. A good measure for numerical comparison of the various cooling rates is obtained if the calorimeter values are plotted on the logarithmic scale versus time. We thereby obtain an arrangement of data points through which a straight line can easily be laid.

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(The true shape of the curve in accordance with Newton's cooling law and the heat transfer conditions at hand can be left out of consideration, with the exception of the material discussed farther below.) The slope of these lines corresponds to the rate of cooling of the body giving up heat; the steeper it is, the higher the transmission of heat and the shorter the time after which the level of heat has dropped below a certain value. The tangents of the slope angles of these lines will be called "cooling value" A in the following. Since such a tangent is obtained by dividing the ordinate, measured in millimeters, by the abscissa, it has no practical dimension and serves merely as a characteristic quantity for the numerical comparison of various heat transmission conditions. For the model hand filled with water at 25° , we obtain an A of 0.910 at a flow rate of 200 cm^2/min (Fig. 4, left). If the coefficients of thermal conductivity and heat transfer always remained the same for other hand heat contents (i.e. greater or lesser temperature differences between hand "content" and calorimeter), the straight line would merely be shifted in parallel fashion, and A would remain unchanged. It is found, however, that A increases with increasing temperature difference (data in the figure caption). This increase in cooling value with increasing temperature difference cannot be attributed to the coefficient of thermal conductivity, since, as a characteristic of the material alone, it has the same value for all four trials. (The slight changes in λ with absolute temperature have been ignored here.) On the other hand, the changes in A correspond quite well to the expected effect of the coefficient of heat transfer, which is not appreciably dependent upon temperature difference or upon absolute temperature; in both cases, α increases with increasing temperature.

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Similarly, a dependence upon flow rate exists for α . In both the laminar and turbulent regions of flow, heat transfer increases with increasing flow rate. To be sure, the steepening of the temperature gradient between hand "content" and calorimeter

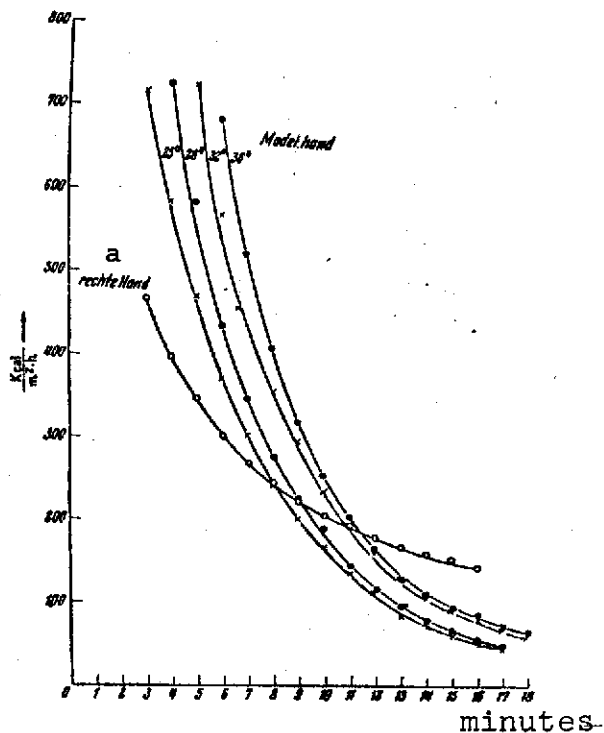


Fig. 3. Cooling curves for the model hand and the unmodified right hand. Flow rate 200 cm³/min. Model hand filled with water at different starting temperatures.

Key: a. Right hand

is made more distinct if the calorimetric value at a particular time on the cooling curve is set equal to 100% and the percentage reduction in heat loss is calculated each minute from there on (Fig. 5 a). In the example selected, heat loss at 2.5 min is initially chosen as the starting point (No. 1). If the result were actually a straight line, it would have to make no difference at what point in time during the trial the loss of heat is set equal to 100% for calculation. The lines constructed from the following 3 min on have increasingly gentler slopes, however; the cooling values calculated in this manner for the

liquid likewise plays a role. Accordingly, those A values are higher which are obtained with a flow of 300 cm³ through the calorimeter. The increase in A associated with the change from 200 to 300 cm³/min calorimeter flow is between 1.2 and 1.9% in the four pairs of trials (Fig. 4). The same increase in cooling value when the temperature difference is increased is calculated for both rates. The percentage increase in A for a 1° increase in temperature difference lies between 0.5 and 1.5%.

As already indicated above, /475 and as also apparent from the data points in Fig. 4, the calorimeter values deviate somewhat from a straight line in the logarithmic plot. This

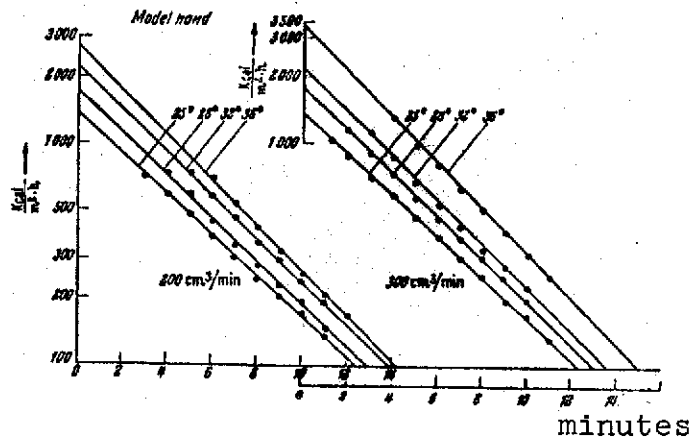


Fig. 4. Model hand. Logarithmic plot of calories given off for various heat contents. The cooling value described in the text is obtained from the tangent of the slope angle for each line. It is the following for the example with 200 cm³/min: 25°: 0.910; 28°: 0.945; 32°: 0.965; 36°: 1.000; for 300 cm³/min: 25°: 0.920; 28°: 0.960; 32°: 0.980; 36°: 1.015.

particular trial are as follows; 0.895, 0.860, 0.860, and 0.845. Thus the later we begin calculating the percentage reduction in heat loss on the curve, the smaller the resultant cooling values will be. The dependence of the coefficient of heat transfer upon temperature difference must also be considered partly responsible for this.

3. Conditions for Determinations of Comparable Cooling Values

The following requirements can be derived from the experimentally confirmed dependence of cooling values upon temperature difference and flow rate; these must be satisfied if different coefficients of heat transfer or thermal conductivity are to be determined on the basis of a comparison of A values: /476

1. for the construction of lines which yield the reference value A, the same calory value must always be selected on the cooling curve to serve as the starting point in order to calculate it from the percentage reduction in heat loss.

2. only curves which have been obtained from trials with the same flow rate may be compared with one another.

When these conditions are satisfied, the effect of starting temperature on the coefficient of heat transfer still does not

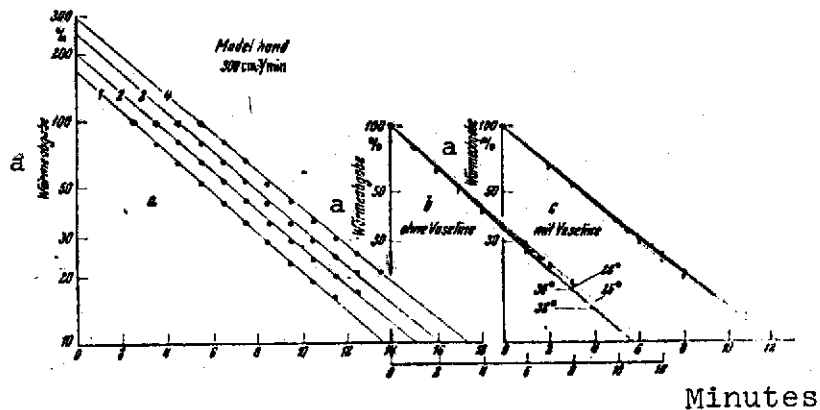


Fig. 5. Model hand. Flow rate $300 \text{ cm}^3/\text{min}$. Cooling value curves constructed by calculating percentage reduction in heat loss from an arbitrary point in time; percentage values plotted logarithmically. a) Percentage values calculated for the same cooling curve, starting at four 1-minute intervals; reduction in cooling value with increasing temperature difference during the course of the trial (numerical values in text). b) and c) Calculation of percentage values for all trials starting from the same number of calories; effect of initial temperature difference and of vasoline on model hand upon cooling value (numerical values in Table 1).

Key: a. Heat loss; b. Without vasoline; c. With vasoline

to the instant of hand immersion; rather, the 0 point is uniformly established at the point in time on the recorded curve at which the specified heat loss was reached. The time value of 0 on the abscissa thus corresponds to a different actual trial time for each of the four lines. In the example at hand, the heat losses had dropped to the specified $800 \text{ Kcal}/(\text{m}^2 \cdot \text{h})$ as follows:

disappear from the resultant lines. In Fig. 5 b, the cooling values corrected in this manner are plotted for the calorimeter curves just shown for four different hand content temperatures. In each of these cases, a heat loss of $800 \pm 10 \text{ Kcal}/(\text{m}^2 \cdot \text{h})$ has been set equal to 100% as the starting point for calculation.

In this graph, as in the following similar graphs, the abscissa thus no longer represents absolute time, in which case 0 would be equivalent

At a starting model hand temperature of 25°:	in 2.5 min
" " " " " "	" 28°: " 3.6 "
" " " " " "	" 32°: " 4.3 "
" " " " " "	" 36°: " 5.0 "

In other words, equal quantities of heat, rather than equal times, were used as the starting points for comparable lines. These "corrected" lines also become steeper as the initial temperature difference increases.

If we wish to use cooling values in this manner to study the effects of surface area changes, which can influence both heat transfer and the coefficient of thermal conductivity, we encounter the following additional requirement:

3. only curves which come from trials with hands at approximately the same starting temperature may be compared with one another.

The cooling values for the lines plotted in Figs. 5 b and c are compiled in Table 1. The second series of trials (c) shows the change in heat transmission caused by coverage with vasoline; this will be treated in a later report. The effect of temperature difference on heat transmission is of the same order of magnitude under various heat transfer conditions. The values for the percentage increase in A per 1° rise in temperature difference are 0.4 to 0.8%, with a narrow dispersion range, i.e. only slightly below the values which were obtained from the original lines of simple construction (Fig. 4). /477

4. Checking the Method

The proper locations of the data points used to construct the lines already support the accuracy of the method applied.

TABLE 1. (REFERS TO FIGS. 5 b AND c)

Initial temp. diff. ($T_1 - T_2$)	Without vasoline		With vasoline		Decrease in A in vasoline trial %
	Increase in A		Increase in A		
	for +1°		for +1°		
	($T_1 - T_2$)		($T_1 - T_2$)		
	%		%		
13,4°	0,890		0,820		— %
16,4°	0,910	+ 0,63	0,835	+ 0,60	— %
20,6°	0,940	+ 0,81	0,870	+ 0,50	9,5
24,6°	0,955	+ 0,40	0,870	+ 0,42	9

[Note: Commas in numerals are equivalent to decimal points.]

It must be taken into consideration here that complete constancy in flow rate could not be expected, due to the formation of air bubbles, and that determination of the starting temperature of the contents of the hand (mercury thermometer several seconds before emersion) can only represent an approximation. The somewhat irregular rightward shift in the lines in Fig. 4 (at 300 cm³/min) might be attributable to this, for instance, as well as the dispersion range of the dependence of A values upon temperature difference derived from the straight lines. For the trials using the untreated model hand, there is a possibility of obtaining an approximate picture of the measurement conditions for this calorimetric method by attempting to determine the coefficient of thermal conductivity of the glass from the quantities of heat lost.

The coefficient of thermal conductivity λ is established in the relation

$$Q = \frac{\lambda \cdot F \cdot (T_1 - T_2)}{\delta} \left[\frac{\text{Kcal}}{\text{m} \cdot \text{h} \cdot \text{C}^\circ} \right] \quad (2)$$

Its calculation thus requires not only determination of the quantity of heat Q flowing through the wall, but also a knowledge

of wall thickness δ , surface area F and effective temperature difference $T_1 - T_2$. If the quantity of heat lost to the outside is measured, rather than that flowing through the wall, then the equation for heat transport must be used:

$$Q = K \cdot F (T_1 - T_2) \left[\frac{\text{Kcal}}{\text{m}^2 \cdot \text{h} \cdot \text{C}} \right] \quad (3)$$

in accordance with the definition of K given earlier, in which λ is contained according to equation (1). By slightly rearranging equation (1), we obtain the following for thermal resistance to transmission:

$$\frac{1}{k} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{\delta}{\lambda} \quad (4)$$

It can be seen from this that the quantity of heat which is /478 lost and which thus flows through the wall is determined not only by thermal resistivity δ/λ but also by resistances to heat transfer $1/\alpha_1$ and $1/\alpha_2$. If optimum heat transfer is assumed, the $1/\alpha$ values, which then become small, can be neglected relative to a high thermal resistivity, and equation (4) finally assumes the form

$$1/k = \delta/\lambda \quad (5)$$

But λ can then be determined from equations (3) and (5). If heat transfer -- as is almost always the case -- plays a measurable role in the entire transmission of heat, however, the λ values which are found must be smaller than the actual coefficient of thermal conductivity.

If these considerations are applied to the case at hand, of a calorimetric cooling curve, we first encounter the problem that the temperature difference to be substituted into equation (3) is

only known accurately at the instant of immersion. The theoretical heat loss associated with this point in time can be obtained by extrapolation if we extend the line drawn through the data points leftward to the ordinate at 0. The intersection of the two lines gives the number of calories which would be lost continually from the model hand if the original temperature difference were maintained.

A more detailed illustration will be given using the trial with the contents of the hand at 25° for a flow rate of 200 cm²/min (Fig. 4, left):

$$\text{Heat loss "at time 0"} = 1350 \text{ Kcal}/(\text{m}^2 \cdot \text{h}).$$

$$\text{Temperature difference} = 25^\circ - 11.8^\circ = 13.2^\circ (T_1 - T_2).$$

Thus for the coefficient of heat transmission we obtain

$$K = 1350/13.2 = 102 \text{ Kcal}/(\text{m}^2 \cdot \text{h} \cdot \text{C}^\circ).$$

Under the assumption of very high heat transfer coefficients, it was now found above that when the resistance to heat transfer is neglected as in equation (5), we may set $K = \lambda/\delta$. Thus $\lambda = K \cdot \delta$. For a mean wall thickness in the model hand of 1.35 mm, we obtain

$$\lambda = 102 \cdot 0.00135 = 0.136 \text{ Kcal}/(\text{m} \cdot \text{h} \cdot \text{C}^\circ).$$

The λ values for the model hand calculated by the method described are as follows for four trials each at flow rates of 200 and 300 cm³/min: 0.138, 0.143, 0.146, 0.150, 0.138, 0.145, 0.144, 0.183. Except for the last value (inaccurate determination of starting temperature), these values fall in the vicinity of 0.143 Kcal/(m·h·C°) with limited dispersion. In the range from 0° to 100°, we find values between 0.6 and 1.0 Kcal/(m·h·C°) (Henning [7]) given for glass.

The improved heat transmission conditions which accompany an increase in temperature difference explain the increase in the coefficients of thermal conductivity which were found. They were generally too low for the following reasons, already discussed:

1. the neglected heat transmission does not play an inconsiderable role. It causes the theoretical quantities of heat lost which are assumed for the instant of immersion to be lower than would be the case if they were determined merely by the coefficients of thermal conductivity. Heat transmission produces an additional resistance which has been included in the calculation of λ .

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2. the values for initial heat loss obtained by extending the lines to the left are also too small because the lines do not correspond to the exact curve.

Nevertheless, the differences between the actual coefficients of thermal conductivity and those found, as well as the dispersion range of the values, are small enough to be taken as evidence of the methodological precision of the setup and as confirmation of the derived mathematics.

Conclusion

The method developed above provides, with sufficient accuracy, characteristic values which express the cooling rates of bodies studied calorimetrically. These cooling values are calculated as the tangents of the slope angle of a straight line which is obtained from a logarithmic plot of the measured calorie values versus time. The cooling values can be used to compare various heat transmission conditions for different bodies with one another in the cooling experiment if the conditions specified in Section 4 are satisfied.

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